AD-A157 475 A SIMULATION OF HIGH LATITUDE F-LAYER INSTABILITIES IN THE PRESENCE OF MAGNETOSPHERE-IONOSPHERE COUPLING(U) NAVAL RESEARCH LAB WASHINGTON DC H G MITCHEEL ET AL. 08 JUL 85 1/1

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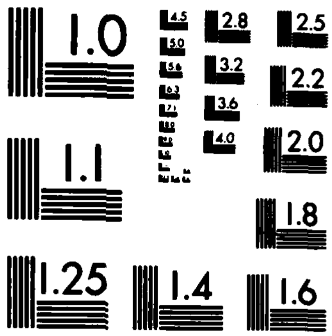

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NRL Memorandum Report 5597

A Simulation of High Latitude F-Layer Instabilities in the Presence of Magnetosphere-Ionosphere Coupling

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July 8, 1985

This research was partially supported by the Defense Nuclear Agency under Subtask QIEQMXBB, work unit 00005, work unit title "Plasma Structure Evolution," and by the National Aeronautics and Space Administration and the Office of the Naval Research.

NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 5597	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory 6b. OFFICE SYMBOL (If applicable) Code 4780	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION DNA, ONR and NASA 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20305 Arlington, VA 22203 Washington, DC 20546	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61153N	(See page ii)		(See page ii)

11. TITLE (Include Security Classification)

A Simulation of High Latitude F-Layer Instabilities in the Presence of Magnetosphere-Ionosphere Coupling

12. PERSONAL AUTHOR(S)

Mitchell, H.G., Jr.,* Fedder, J.A., Keskinen, M.J. and Zalesak, S.T.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Interim	FROM ______ TO ______	1985 July 8	30

16. SUPPLEMENTARY NOTATION

*Science Applications International Corporation, McLean, VA 22102 (Continues)

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Ionospheric structure, Magnetosphere-ionosphere coupling, High latitude ionosphere, Interchange instabilities nu sub i << omega

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A magnetic-field-line-integrated model of plasma interchange instabilities is developed for the high latitude ionosphere including magnetospheric coupling effects. We show that the primary magnetosphere-ionosphere coupling effect is to incorporate the inertia of the magnetospheric plasma in the analysis. As a specific example, we present the first simulation of the $E \times B$ instability in the inertial regime, i.e., $\nu_i << \omega$ where ν_i is the ion-neutral collision frequency and ω is the wave frequency. We find that the inertial $E \times B$ instability develops in a fundamentally different manner than in the collisional case ($\nu_i >> \omega$). Our results show that striations produced in the inertial regime are spread and retarded by ion inertial effects, and result in more isotropic irregularities than those seen in the collisional case. Keywords:

nu sub i omega >> omega

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL J. D. Huba	22b. TELEPHONE (Include Area Code) (202) 767-3630 22c. OFFICE SYMBOL Code 4780

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

10. SOURCE OF FUNDING NUMBERS

PROJECT NO.	WORK UNIT ACCESSION NO.
RR033-02-44	S-14534-0
85-550	DN480-935
	DN580-072

16. SUPPLEMENTARY NOTATION (Continued)

This research was partially supported by the Defense Nuclear Agency under Subtask QIEQMXBB, work unit 00005, work unit title "Plasma Structure Evolution," and by the National Aeronautics and Space Administration and the Office of Naval Research.

CONTENTS

A SIMULATION OF HIGH LATITUDE F-LAYER INSTABILITIES IN THE PRESENCE OF MAGNETOSPHERE-IONOSPHERE COUPLING

I. INTRODUCTION

Recent experimental ground-based, rocket, and satellite (HILAT, DYNAMICS EXPLORER, AUREOL-3) observations in the auroral zone and polar cap ionosphere have indicated the existence of both large [Weber et al., 1984; Basu et al., 1984; Bythrow et al., 1984; Cerisier et al., 1984; Vickrey et al., 1980] and small [Hanuise et al., 1981; Baker et al., 1983] scale density structures and irregularities. Different mechanisms, have been proposed to account for high latitude ionospheric irregularities, e.g., particle precipitation, plasma instabilities, and neutral fluid turbulence [Keskinen and Ossakow, 1983]. Considerable quantitative progress has been made in explaining ionospheric structure using plasma interchange instabilities, e.g., the Rayleigh-Taylor instability [Balsley et al., 1972; Ossakow, 1981] in equatorial spread F, and the $\underset{\sim}{E} \times \underset{\sim}{B}$ and current-convective instabilities in the high latitude ionosphere [Ossakow and Chaturvedi, 1979; Keskinen and Ossakow, 1983]. Recently, Weber et al. (1984) and Cerisier et al. (1984) have invoked the $\underset{\sim}{E} \times \underset{\sim}{B}$ instability to explain large scale density fluctuations in the high latitude ionosphere.

A shortcoming of most past research on the nonlinear theory of the $\underset{\sim}{E} \times \underset{\sim}{B}$ instability as it applies to ionospheric structure is that it has been restricted to the collisional (or non-inertial) regime, i.e., $\nu_i >> \omega$ where ν_i is the ion-neutral collision frequency and ω is the wave frequency. One exception is the recent work of Huba et al. (1985) who studied the nonlinear evolution of interchange instabilities in both the inertial and non-inertial regimes. However, their work was limited to short wavelength turbulence, i.e., $kL >> 1$ where k is the wavenumber and L is the density gradient scale length, which is not applicable to large scale ionospheric structures.

In this letter, we present the first simulation of inertial high latitude ionospheric interchange instabilities (e.g., the $\underset{\sim}{E} \times \underset{\sim}{B}$ instability) with inclusion of magnetospheric coupling effects. The basic conclusions of this study are (1) magnetospheric coupling effects reduce the growth rate of the $\underset{\sim}{E} \times \underset{\sim}{B}$ instability, (2) striations produced by the inertial $\underset{\sim}{E} \times \underset{\sim}{B}$ instability develop in a different manner than in the non-

Manuscript approved April 17, 1985.

inertial ($\nu_i >> \omega$) regime, (3) in configuration space, the striations in the inertial regime are more isotropic and spread out resulting in irregularities oriented perpendicular to those produced in the non-inertial case.

II. MODEL

The physical configuration and assumptions of our model are described as follows. We only consider structure in the plane transverse to the ambient magnetic field, i.e., the xy plane. The F-layer is initially characterized by a 6 to 1 density enhancement with a Gaussian profile of scale size 12 km in the x-direction and uniform in the y-direction, a uniform magnetic field in the z-direction (B_z = 0.5 G), and a background electric field in the y-direction (E_y = .025 V/m). The entire enhancement $\underline{E} \times \underline{B}$ drifts in the x-direction at a velocity v_x = 0.5 km/sec. A uniform horizontal magnetosphere is assumed above the F-layer linked by the vertical magnetic field lines. The back edge of the F-layer enhancement, relative to the drift, is unstable to the $\underline{E} \times \underline{B}$ instability, which drives ion Pedersen currents in the F-layer and ion polarization drift currents in the magnetosphere due to the perpendicular electric field mapping along the geomagnetic field. These currents close along the magnetic field via parallel electron currents. Assuming that all ion drifts associated with the perpendicular currents are negligible compared to the $\underline{E} \times \underline{B}$ drift and that $\underline{E}_\perp = -\nabla_\perp \phi$, the equations describing this system are

$$\frac{\partial n}{\partial t} + \nabla_\perp \cdot n\underline{v}_{i_\perp} = 0 \tag{1}$$

$$\underline{v}_{e_\perp} = \underline{v}_{i_\perp} = - \frac{c\nabla_\perp \phi}{B} \times z \tag{2}$$

$$\underline{j}_{F_\perp} = - \left(\frac{cne\nu_i}{B\Omega_i}\right) \nabla_\perp \phi = - \sigma_p \nabla_\perp \phi \tag{3}$$

$$\underline{j}_{M_\perp} = - \frac{1}{4\pi} \left(\frac{c^2}{V_A^2}\right)\left[\frac{\partial}{\partial t} + \underline{v}_{i_\perp} \cdot \nabla_\perp\right] \nabla_\perp \phi \tag{4}$$

$$0 = \int_F dz \left(\nabla_\perp \cdot \underline{j}_{F_\perp}\right) + \int_M dz \left(\nabla_\perp \cdot \underline{j}_{M_\perp}\right) \tag{5}$$

where n is the ion (and electron) density, $\underline{v}_{e(i)\perp}$ is the perpendicular electron (ion) velocity, $\underline{j}_{F\perp}$ and $\underline{j}_{M\perp}$ are the F-layer Pedersen and the magnetospheric polarization drift current densities, respectively, σ_p is the F-layer Pedersen conductivity, $V_A = B/(4\pi n m_i)^{1/2}$ is the Alfvén velocity, and ν_i and Ω_i are the ion-neutral collision frequency and ion gyrofrequency, respectively. Using (2)-(4) in (5) yields the potential equation,

$$0 = \nabla_\perp \cdot \{\Sigma_p + C_M[\frac{\partial}{\partial t} - (\frac{c\nabla_\perp\phi}{B} \times z) \cdot \nabla_\perp]\}\nabla_\perp\phi \tag{6}$$

where the field-line integrated F-layer Pedersen conductivity is

$$\Sigma_p = \int_F dz\ \sigma_p, \tag{7}$$

and the field-line integrated magnetospheric inertial capacitance is

$$C_M = \frac{1}{4\pi} \int_M dz\ (c^2/V_A^2). \tag{8}$$

Since the magnetospheric layer is uniform and the ion flow given by (2) is incompressible, the magnetosphere remains uniform and the continuity equation for this layer may be neglected. The F-layer continuity equation for n may be written as a continuity equation for Σ_p,

$$\frac{\partial}{\partial t} \Sigma_p + \nabla_\perp \cdot (\Sigma_p \underline{v}_{i_\perp}) = 0. \tag{9}$$

Therefore, the system is completely described by (2), (6) and (9) in the variables Σ_p and ϕ, with C_M a constant capacitance describing the magnitude of magnetosphere-ionosphere coupling.

The numerical methods used to simulate the model equations are described in Zalesak et al. [1982]. The continuity equation (9) is solved numerically using the multi-dimensional flux-corrected techniques of Zalesak [1979], while the potential equation (6) is solved with the incomplete Cholesky conjugate gradient algorithm of Hain [1980]. The simulations are performed on an 100 x 80 cell grid (x,y) with a cell size of 1.0 km x .25 km which is drifting with the enhancement at the $E_y \times B$ velocity. Periodic boundary conditions are assumed in the y-direction, and the grid is initialized with a random 1% density fluctuation.

If Σ_p has scale length $L^{-1} = (1/\Sigma_p)\partial\Sigma_p/\partial x$, the non-inertial ($C_M = 0$) growth rate for a wave with wave vector k parallel to y is $\gamma_0 = cE_y/BL$ in the regime $kL \gg 1$. For the parameters of our simulation, the maximum (non-inertial) growth rate is $\gamma_0 \approx 0.05$ sec^{-1}. The e-folding distance of $E_\perp$ parallel to B for this wave is about $\lambda_\parallel \sim (\sigma_\parallel/\sigma_\perp)^{1/2}k_\perp^{-1}$ [Völk and Haerendel, 1971], implying that a wave with $k_\perp^{-1} = 1$ km has an e-folding distance of 10^3 km parallel to the field and that $E_\perp$ maps well up into the magnetosphere where the e-folding distance is much greater due to the rapid decrease in σ_p. The Alfvén speed is $V_A \sim 10^3$ km/sec so that electric fields of a wave with a growth time of 20 sec map upwards on the order of 10^4 km into the magnetosphere, and C_M has a value of roughly 10^{13} cm (or ~ 10 farad).

The effect of ion inertia on the $\underset{\sim}{E} \times \underset{\sim}{B}$ instability has previously been studied by Ossakow et al. [1978] in the linear regime. Although their results were for Pedersen and polarization drifts at the same altitude, the linear growth rates are effectively the same for our model equations. A non-zero inertia implies the existence of an inertial relaxation rate, $\gamma_i = \Sigma_p/C_M$. The growth rate in the presence of inertia for the short wavelength approximation has two regions of interest, the non-inertial regime

$$\gamma = \gamma_0 \qquad \text{for} \qquad 4\gamma_0 \ll \gamma_i \tag{10}$$

and the inertial regime

$$\gamma \approx (\gamma_0\gamma_i)^{1/2} \qquad \text{for} \qquad 4\gamma_0 \gg \gamma_i . \tag{11}$$

Assuming a Σ_p for the F-layer of 8 x 10^{10} cm/sec (~ 0.1 mho), a typical value of γ_i for the simulation is .008 sec^{-1}, which is in the inertial regime and which reduces the growth rate of the instability from .05 sec^{-1} to .02 sec^{-1}. For our simulation, two cases were run: a non-inertial case for which $\gamma_i = 1.00$ sec^{-1}, and an inertial case for which $\gamma_i = 0.01$ sec^{-1}.

III. RESULTS

The results of the two simulations are shown in Figures 1 and 2. The four panels in each simulation show approximately equal times relative to the linear growth time of the instability. Figure 1 shows the results for the non-inertial $\underset{\sim}{E} \times \underset{\sim}{B}$ instability, while Figure 2 shows the results for the inertial case. It is clear that the results of the two cases are very different at later times.

The behavior of the plasma in Figure 1 is typical of that observed in previous $\underset{\sim}{E} \times \underset{\sim}{B}$ instability simulations [Keskinen and Ossakow, 1982]. In panel 2, at 104 seconds, we see that early in the nonlinear stage a set of "fingers" has clearly formed. The high density fingers grow outward into the low density plasma while the low density fingers penetrate into the high density cloud. Subsequent nonlinear evolution involves the continued elongation of these fingers with very little apparent change in the size of the structures perpendicular to their long dimension as seen in panels 3 and 4. The original density enhancement has effectively been sliced into a group of sheets parallel to the initial density gradient.

The behavior of plasma and structure formation in Figure 2, the inertial case, is very different. During the time period between panel 1 and panel 2, before 300 seconds, the growth of the instability closely resembles that in Figure 1. There is nonlinear development of long narrow high and low density fingers which move in opposite directions. However, after 300 seconds, the behavior changes radically. In panels 3 and 4, we see that the fingers form mushroom-like heads and tend to thicken. No longer are there long thin interpenetrating fingers, rather they are fat interpenetrating blobs. Any narrow fingers which begin to form quickly go to a mushroom shape and then spread out. In a number of simulations we have noted a tendency for the structure in the y direction to undergo an inverse cascade to the longest mode which will fit in the system. This feature can clearly be seen in panel 4, where the structured state throughout most of the simulation region shows two blobs; one of high density, the other of low density.

The non-inertial simulation, shown in Figure 1, is characterized by striations with a large value of k_y, which grow in the x-direction without hindrance, completely destroying the initial orientation of the density

enhancement in the y-direction. The inertial simulation, shown in Figure 2, is characterized initially by striations with a large value of k_y, which are hindered in their growth in the x-direction. The plasma at the leading edge of the striation finger is swept to either side and around the striation forming the characteristic mushroom shape. Further evolution involves an inverse cascade in k_y to the minimum value allowed on the numerical grid while simultaneously, the typical value of k_x increases. Consequently, individual enhancements tend to an orientation similar to the original x-directed orientation. Furthermore, the individual enhancements appear to be stabilized to further $\underset{\sim}{E} \times \underset{\sim}{B}$ structuring owing to velocity shear along their apparently unstable faces (Perkins and Doles, 1975; Huba et al., 1983).

Interestingly, Rino et al. (1979), Livingston et al. (1982), and Rino and Vickrey (1982) have reported sheet-like structures in the night side auroral region which are aligned perpendicular to the large scale F region ionospheric density gradient. This alignment perpendicular to the density gradient is not easily explained by the traditional instability theory. However, the alignment is similar to the final alignment observed in the inertial simulations.

IV. CONCLUDING REMARKS

Several conclusions can be drawn from our simulations. First, instability-generated electric fields in the high-latitude F-layer may map well up into the magnetosphere, resulting in a much reduced linear growth rate due to the effectively increased ion inertia. Second, the nonlinear development of the instability is fundamentally different in the presence of this coupling; the striations produced are spread and retarded by ion-inertial effects resulting in more isotropic irregularities than in the non-inertial case. The inertial effects may even tend to stabilize the final nonlinear state by producing a velocity shear across normally unstable gradients. The simulation results demonstrate some interesting features which may have been observed in the high latitude nighttime ionosphere.

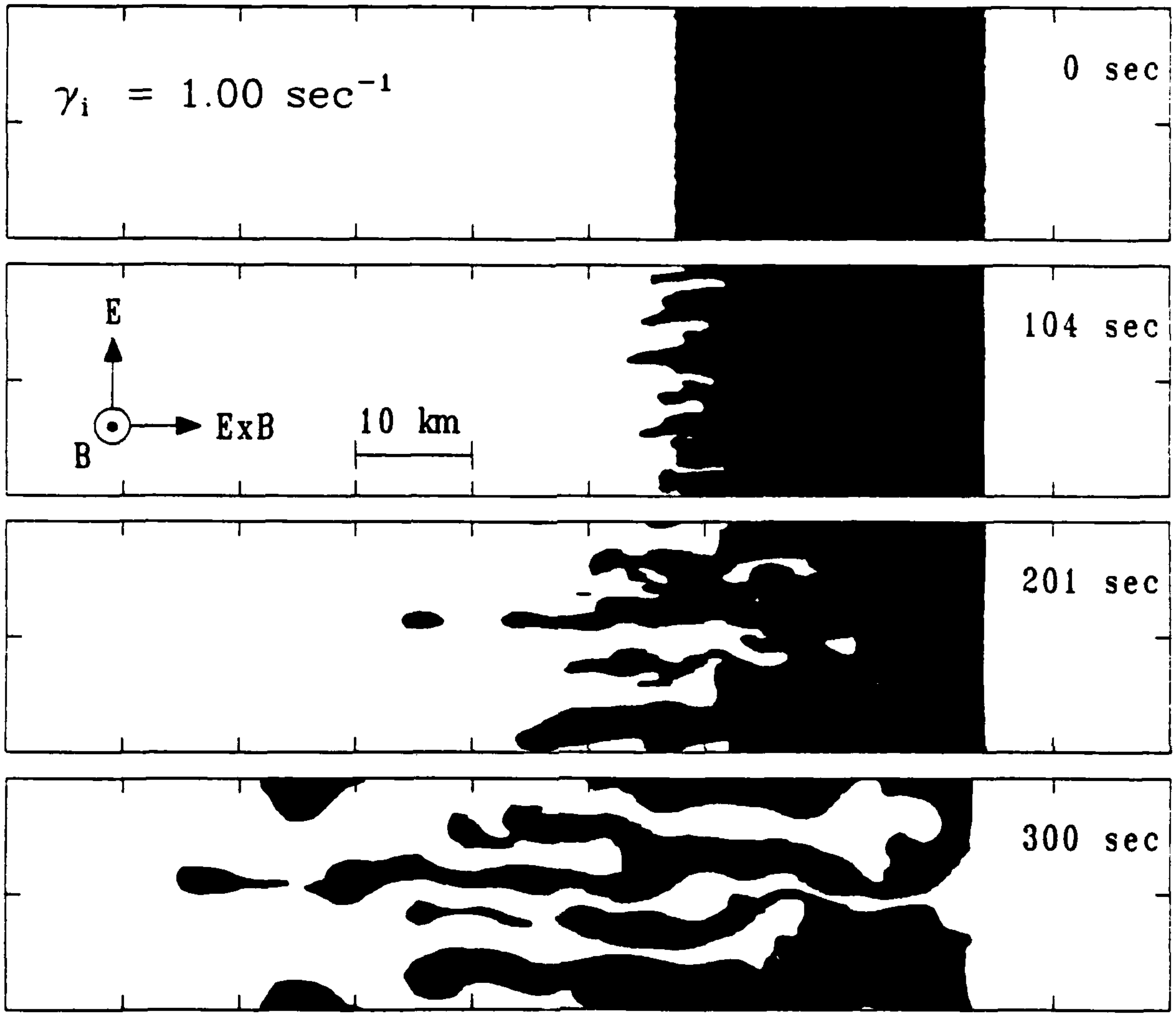

Fig. 1. A plot of density for four times for the case of $\gamma_i = 1.00\ sec^{-1}$ (the non-inertial case). The shaded region represents those areas whose density is greater than 2.5 times the background density. The simulation grid is periodic in the direction of $\underset{\sim}{E}$ and is moving with the $\underset{\sim}{E} \times \underset{\sim}{B}$ velocity.

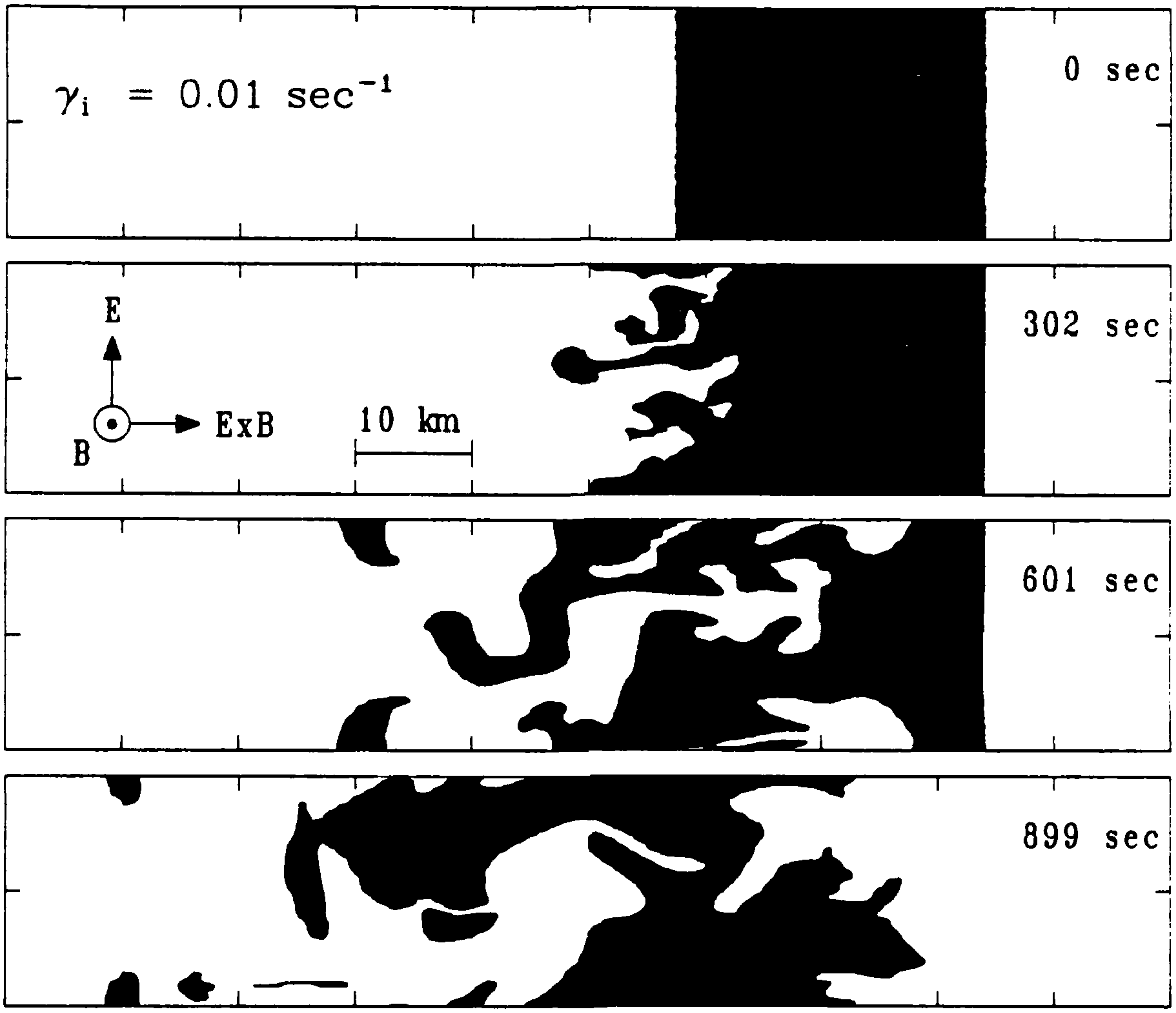

Fig. 2. A plot of density for four times for the case of $\gamma_i = 0.01$ sec^{-1} (the inertial case). The shaded region and the simulation grid are the same as in Fig. 1. The times shown in the two figures are roughly equal multiples of the linear growth time for the instability in the two cases.

Acknowledgments

We thank Dr. J.D. Huba for helpful discussions and a critical reading of the manuscript. This research was supported by the Defense Nuclear Agency, the National Aeronautics and Space Administration, and the Office of Naval Research.

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